# Robust laser cooling of trapped systems

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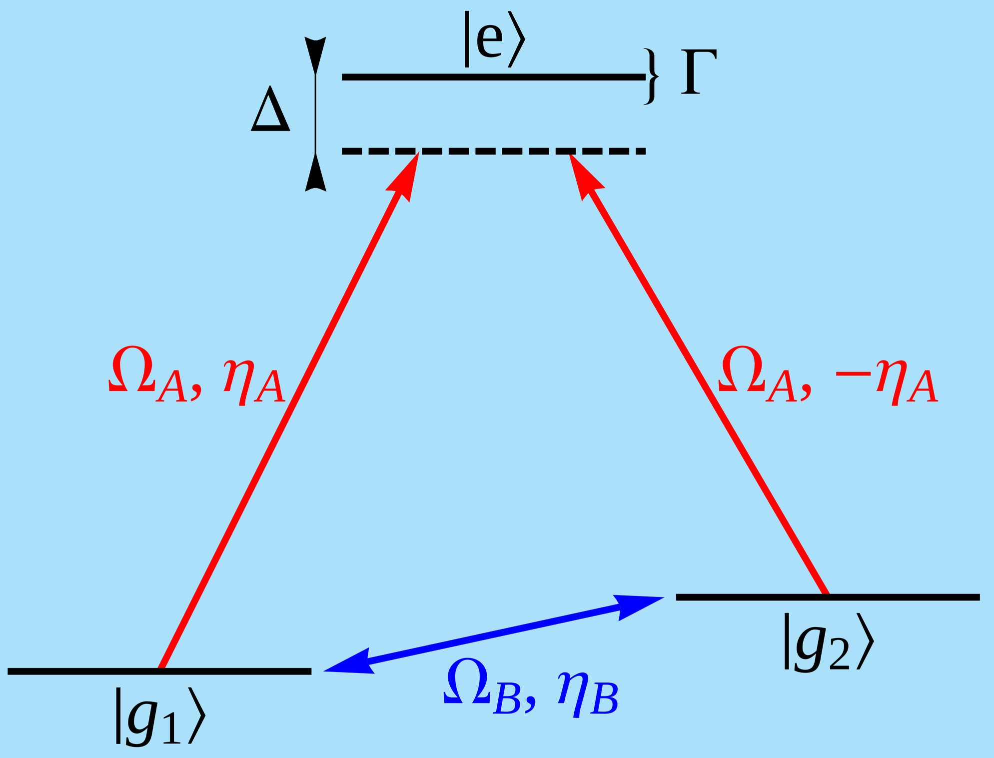
## Introduction

We present a robust and fast laser cooling scheme suitable for trapped systems. Based on quantum interference, generated by a special laser configuration, it is able to rapidly cool the system such that the final phonon occupation vanishes to zeroth order in the Lamb-Dicke parameter in contrast to existing cooling schemes. Furthermore, it is robust under conditions of fluctuating laser intensity and frequency, thus making it a viable candidate for experimental applications.

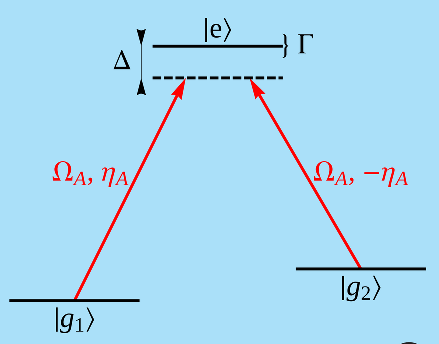
## System

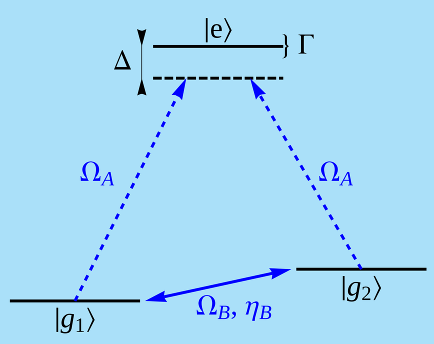



Three level system coupled by (A) a Raman pair of lasers and (B) a coupling of ground levels, harmonically trapped at frequency $\nu$.

## Precedents

EIT cooling | Stark shift cooling




Conditions

$\Omega_B, \eta_B \to 0$ $\qquad$ $\eta_A \to 0$

$\Omega_A^2 = \nu(\Delta - \nu)$ $\qquad$ $\Omega_B = \dfrac{\nu}{2}$

Cooling Rate

$W_{max} \propto \dfrac{\eta_A^2}{\gamma}$ $\qquad$ $W_{max} < \dfrac{\eta_B^2 \nu^2 \gamma}{8\Omega_A^4}$

Steady State

In both schemes it is a **mixture** with contribution from $n > 0$ levels:

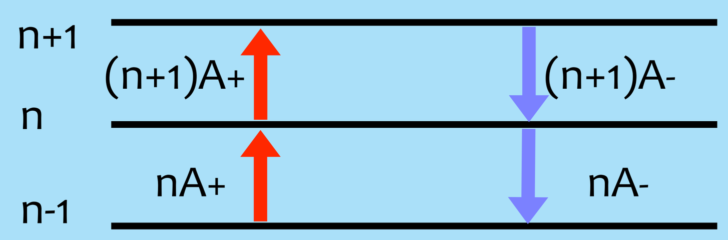
$$\rho = |dark\rangle\langle dark| \otimes \sum_n a_n |n\rangle\langle n| + o(\eta^2) \qquad (1)$$

Final Temperature

The mixture generates finite temperature at zeroth order in the Lamb - Dicke expansion:

$$\langle n\rangle_\infty \simeq \mathbf{n_0} + o(\eta^2) \qquad (2)$$

## Null Heating Rate




Master Equation
↓
Adiabatic elimination of internal dof
↓
Heating & Cooling rates ($A_+$ & $A_-$)

$$A_+ = 0. \qquad (3)$$

## Purity of Steady State

**Pure** steady state:

$$\rho = |dark\rangle\langle dark| \otimes |\mathbf{0}\rangle\langle\mathbf{0}| + o(\eta^2) \qquad (4)$$

Even at higher orders:

$$|\Psi\rangle = |g_1 - g_2\rangle|0\rangle - i\eta_A|g_1 + g_2\rangle|1\rangle + o(\eta^2). \qquad (5)$$

This is a Hamiltonian eigenstate if:

$$\frac{\eta_B}{\eta_A} = \left(\frac{\nu}{\Omega_B} + 2\right). \qquad (6)$$

## Final Temperature & Interference Mechanism

$$H = H_{EIT} + H_{SSh}$$

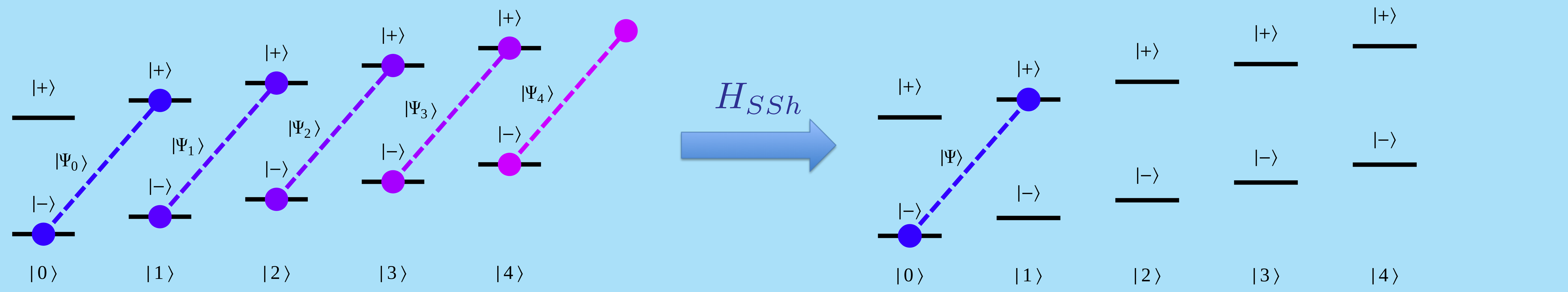
$$H_{EIT} = \Omega_A\left(\sigma_x^{g_1,e} + \sigma_x^{g_2,e}\right) + \eta_A\Omega_A\left(\sigma_y^{g_1,e} - \sigma_y^{g_2,e}\right)(b + b^\dagger)$$

$$H_{SSh} = \nu b^\dagger b + \textstyle\sum_i \omega_i |i\rangle\langle i| + \Omega_B\sigma_x^{g_1,g_2} + \eta_B\Omega_B\sigma_y^{g_1,g_2}(b + b^\dagger)$$

The EIT part has a degenerate eigenspace for eigenvalue 0 that the SSh part doesn't share.

$H_{EIT}|\Psi_n\rangle = 0$ $\qquad$ $H_{SSh}|\Psi_n\rangle \neq a|\Psi_n\rangle$

$|\Psi_0\rangle \equiv |\Psi\rangle$ → tuning parameters as in (6) → $H_{SSh}|\Psi_n\rangle = a|\Psi_n\rangle$ → **degeneracy breaks**

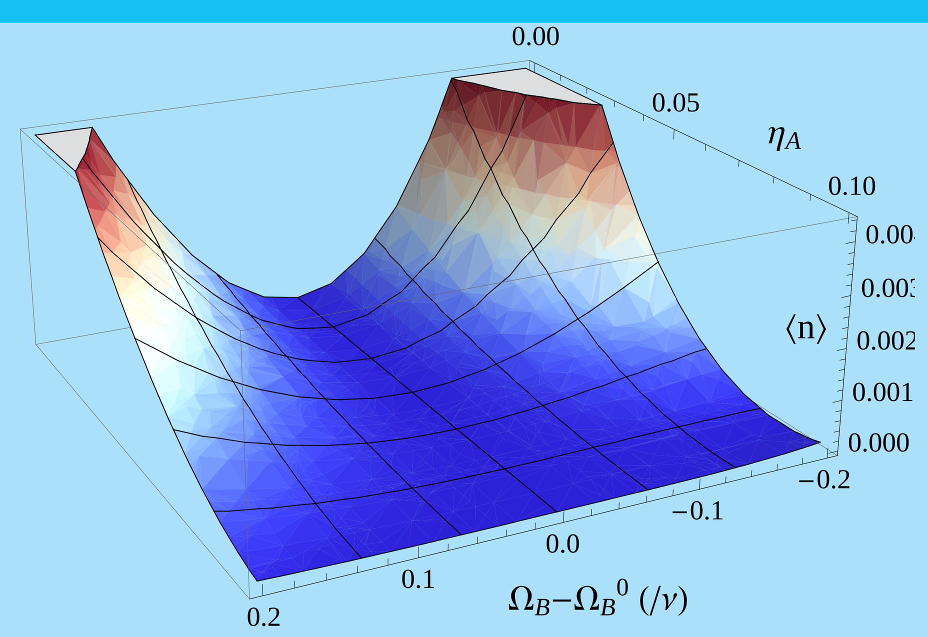



Unlike (2), interference makes **temperature vanish** at zeroth order in the Lamb - Dicke parameter:

$$n_0 = 0$$

Cooling rate ($W = A_- - A_+$): $W_{max} \propto \dfrac{\eta_B^2\nu^2\gamma}{8\Omega_A^4}$

## Robustness



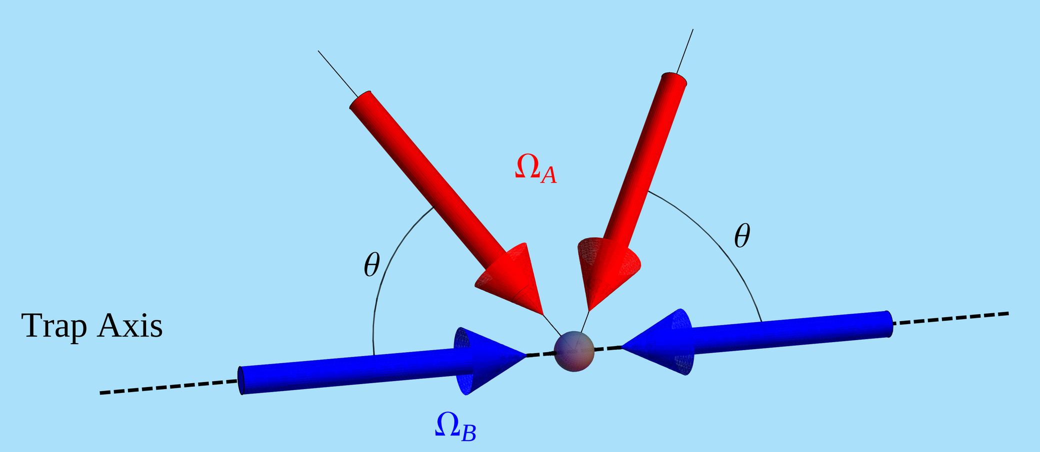

Dependence on parametric fluctuation:

$$\langle n\rangle_\infty \propto (\Delta\Omega_A)^4(\Delta\Omega_B)^2 \qquad (7)$$

## Implementation

2 pairs of Raman beams, where:

$$\frac{\eta_B}{\eta_A} = \frac{2}{\cos\theta} \qquad (8)$$




Also: magnetic gradients.

## Scope

Trapped Ions $\qquad$ Neutral Atoms $\qquad$ Nanomechanical Oscillators

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## References

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